

# Baryogenesis via lepton number violation in Anti-GUT model

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## Abstract

We study the baryogenesis via lepton number violation in the model of Anti-GUT. The origin of the baryogenesis is the existence of right-handed Majorana neutrinos which decay in a  $C$ ,  $CP$  and lepton number violation way. The baryon number asymmetry is calculated in the extended Anti-GUT model which is only able to predict order of magnitude-wise. We predicted baryon number to entropy ratio,  $Y_B = 1.46^{+5.87}_{-1.17} \times 10^{-11}$ , and this result agrees with experimental values very well.

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# 1 Introduction

The evidence of the neutrino masses and its mixing angles from the atmospheric and solar neutrino experiments [1, 2, 3, 4, 5, 6, 7, 8, 9] indicates a method to solve a challenging question in cosmology and particle physics: namely, baryon asymmetry of the Universe. This asymmetry cannot be explained with the “pure” Standard Model (SM) – with negligible  $B - L$  asymmetry – to the phenomenologically right magnitude of baryogenesis. In fact, the electroweak phase transition scenario for baryogenesis does not work very well in the frame of the SM with presently known lower bound of the SM Higgs mass [10]. Even for the minimal supersymmetric standard model (MSSM) this scenario is strongly disfavoured by baryon number wash-out at the electroweak phase transition [11]. More detailed analyses of the MSSM [12] have been made and it is claimed that the MSSM is just consistent with baryogenesis in a very restricted region of parameter space requiring the right-handed stop to be lighter than the top quark and the left-handed stop heavier than 1 TeV.

The model which we investigate in the present article – the extended Anti-GUT model – has as one of its characteristics that it coincides with the pure SM (at least) for energy scales below the see-saw neutrino scale, and so we have in this model no way to get the phenomenological baryon number unless we already have an  $B - L$  asymmetry prior to the weak epoch.

However in the SM the neutrinos are massless due to the weak gauge symmetry or the conservation of the lepton number ( $L$ ) and therefore the observed neutrino masses imply the existence of the new scale – the only well-known scales, *i.e.* weak, strong and Planck scales, alone are not able to provide this scale. A very suggestive mechanism is the see-saw mechanism [13].

In our extended Anti-GUT [14] model the see-saw mechanism is already built in as far as we assume the existence of the three right-handed neutrinos – Majorana neutrinos – in the range of a new scale in the order of  $10^{12}$  GeV, and the predictions of this model are very successful for the small mixing angle MSW [15] (SMA-MSW) scenario.

Sakharov [16] has pointed out that a matter-anti-matter asymmetry can be dynamically generated in an expanding Universe if the particle interactions and the cosmological evolution satisfy the three conditions: (1) baryon number violation, (2)  $C$  and  $CP$  violation, (3) departure from thermal equilibrium. The Anti-GUT model is a natural extension model of the SM in which  $C$  and  $CP$  are already violated, *i.e.* this model satisfies if combined with the standard cosmology all these Sakharov’s conditions, therefore the baryon number asymmetry should be predictable with this model in the scenario that the three Majorana neutrinos are very heavy and that they violate the lepton number conservation during their out-of-equilibrium decays in the early stage of the Universe: Baryogenesis via lepton number violation [17].

The presently “observed” baryon asymmetry, the baryon density-to-entropy density ratio of the Universe,

$$Y_B \equiv \frac{n_B - n_{\bar{B}}}{s} = (1.0 - 10) \times 10^{-11} , \quad (1)$$

is with the Universe evolution explained as consequence of the spectrum and interactions of the particles which break the linear combination of the baryon number ( $B$ ) and lepton number,  $B - L$ , global symmetry at high temperature.

In the following section, we should review briefly the Anti-GUT model to calculate the baryogenesis. Then, in the next section, we shall discuss the scenario of the baryogenesis via lepton number violation. In section 4 we present the results of our model. Section 5 contains our conclusion and

## 2 The extended Anti-GUT model

In this section we shall review briefly the extended Anti-GUT model [14]. The extended Anti-GUT model is based on a large gauge group which is the Cartesian product of family specific gauge groups, namely,

$$\prod_{i=1,2,3} (SMG_i \times U(1)_{B-L,i}) , \quad (2)$$

where  $SMG_i$  denotes  $SU(3)_i \times SU(2)_i \times U(1)_i$  (SM gauge group), and  $i$  denotes the generation, *i.e.* each “proto-family” has a certain subgroup of the grand unification group,  $SO(10)$ . This group in Eq. (2) consist only of those representations that do not mix the different irreducible representation of the SM and is spontaneously breaking down to the  $SU(3) \times SU(2) \times U(1) \times U(1)_{B-L}$  at the scale about 1 to 2 orders of magnitude under the Planck scale. The breaking is supposed to occur

Table 1: All  $U(1)$  quantum charges in extended Anti-GUT model.

	$SMG_1$	$SMG_2$	$SMG_3$	$U_{B-L,1}$	$U_{B-L,2}$	$U_{B-L,3}$
$u_L, d_L$	$\frac{1}{6}$	0	0	$\frac{1}{3}$	0	0
$u_R$	$\frac{2}{3}$	0	0	$\frac{1}{3}$	0	0
$d_R$	$-\frac{1}{3}$	0	0	$\frac{1}{3}$	0	0
$e_L, \nu_{eL}$	$-\frac{1}{2}$	0	0	-1	0	0
$e_R$	-1	0	0	-1	0	0
$\nu_{eR}$	0	0	0	-1	0	0
$c_L, s_L$	0	$\frac{1}{6}$	0	0	$\frac{1}{3}$	0
$c_R$	0	$\frac{2}{3}$	0	0	$\frac{1}{3}$	0
$s_R$	0	$-\frac{1}{3}$	0	0	$\frac{1}{3}$	0
$\mu_L, \nu_{\mu L}$	0	$-\frac{1}{2}$	0	0	-1	0
$\mu_R$	0	-1	0	0	-1	0
$\nu_{\mu R}$	0	0	0	0	-1	0
$t_L, b_L$	0	0	$\frac{1}{6}$	0	0	$\frac{1}{3}$
$t_R$	0	0	$\frac{2}{3}$	0	0	$\frac{1}{3}$
$b_R$	0	0	$-\frac{1}{3}$	0	0	$\frac{1}{3}$
$\tau_L, \nu_{\tau L}$	0	0	$-\frac{1}{2}$	0	0	-1
$\tau_R$	0	0	-1	0	0	-1
$\nu_{\tau R}$	0	0	0	0	0	-1
$\phi_{WS}$	$\frac{1}{6}$	$\frac{1}{2}$	$-\frac{1}{6}$	$-\frac{2}{3}$	1	$-\frac{1}{3}$
$S$	$\frac{1}{6}$	$-\frac{1}{6}$	0	$-\frac{2}{3}$	$\frac{2}{3}$	0
$W$	$-\frac{1}{6}$	$-\frac{1}{3}$	$\frac{1}{2}$	$\frac{2}{3}$	-1	$\frac{1}{3}$
$\xi$	$\frac{1}{3}$	$-\frac{1}{3}$	0	$-\frac{1}{3}$	$\frac{1}{3}$	0
$T$	0	$-\frac{1}{6}$	$\frac{1}{6}$	0	0	0
$\chi$	0	0	0	0	-1	1
$\phi_{B-L}$	$-\frac{1}{6}$	$\frac{1}{6}$	0	$\frac{2}{3}$	$-\frac{2}{3}$	2

by six Higgs fields which we have invented and denoted by the symbols  $S$ ,  $W$ ,  $T$ ,  $\xi$ ,  $\chi$  and  $\phi_{B-L}$  and their quantum numbers are given in Table 1. Finally the breaking of  $SU(2) \times U(1)$  of the SM is broken by Weinberg-Salam Higgs field,  $\phi_{WS}$ . (also its quantum numbers are found in Table 1.)

We summarise here the vacuum expectation values (VEV) of the seven Higgs fields which the model contains:

- 1) The smallest VEV Higgs field is the Standard Model Weinberg-Salam Higgs field,  $\phi_{WS}$ , with the VEV at the weak scale being  $246 \text{ GeV}/\sqrt{2}$ .
- 2) The next smallest VEV Higgs field is also alone in its class and breaks the common  $B-L$  gauge group  $U(1)_{B-L}$ , common to the all the families. This symmetry is supposed to be broken (Higgsed) at the see-saw scale as needed for fitting the over all neutrino oscillation scale. This VEV is of the order of  $10^{12} \text{ GeV}$  and called  $\phi_{B-L}$ .
- 3) The next 4 Higgs fields are called  $\xi$ ,  $T$ ,  $W$ , and  $\chi$  and have VEVs of the order of a factor 10 to 50 under the Planck unit. That means that if intermediate propagators have scales given by the Planck scale, as we assume, they will give rise to suppression factors of the order  $1/10$  each time they are needed to cause a transition.
- 4) The last one, with VEV of the same order of the Planck scale, is the Higgs field  $S$ , which gives little suppression when it is applied, of the order of a factor  $1/\sqrt{2}$ .

The quantum numbers of the 45 well-known Weyl particles and additional three particles - Majorana neutrinos - are gotten from the requirement that all anomalies evolving  $U(1)_{B-L,1}$ ,  $U(1)_{B-L,2}$ ,  $U(1)_{B-L,3}$  vanish strongly even without using Green-Schwarz anomaly cancellation mechanism [18], *i.e.* the extended Anti-GUT model is an anomaly free model. These quantum numbers are also shown in Table 1.

Now we can write down the mass matrices which are necessary to discuss the mechanism of baryogenesis in the following sections: the Dirac neutrino mass matrix and the Majorana neutrino mass matrix. These matrix elements were gotten using the technical corrections, factorial factor corrections,  $\sqrt{\# \text{ diagrams}}$  multiplying the mass matrix elements which take into account the possibilities of permuting the contributing Higgs fields. With this technical correction and the quantum charges of the Higgs fields the mass matrices, Dirac neutrino and the Majorana neutrino, are given by:

$$M_\nu^D \sim \frac{\langle \phi_{WS} \rangle}{\sqrt{2}} \begin{pmatrix} 6\sqrt{35} S W T^2 \xi^2 & 60\sqrt{14} S^3 W T^2 \xi^3 & 60\sqrt{154} S^3 W T^2 \xi^3 \chi \\ 6\sqrt{35} S^2 W T^2 \xi & 2\sqrt{3} W T^2 & 2\sqrt{15} W T^2 \chi \\ 6\sqrt{70} S^2 W T \xi \chi & 2\sqrt{6} W T \chi & \sqrt{6} W T \end{pmatrix} \quad (3)$$

$$M_R \sim \langle \phi_{B-L} \rangle \begin{pmatrix} 2\sqrt{210} S^3 \chi^2 \xi^2 & \sqrt{15} S \chi^2 \xi & \sqrt{6} S \chi \xi \\ \sqrt{15} S \chi^2 \xi & \sqrt{6} S \chi^2 & \sqrt{\frac{3}{2}} S \chi \\ \sqrt{6} S \chi \xi & \sqrt{\frac{3}{2}} S \chi & S \end{pmatrix}. \quad (4)$$

We know neither the Yukawa couplings nor the precise masses of the fundamental fermions, but it is a basic assumption of the naturalness of our model that these couplings are of order unity and random complex in the Planck scale. In the numerical evaluation of the consequences of the model we explicitly take into account these uncertain factors of order unity by providing each matrix

element with an explicit random number  $\lambda_{ij}$  - with a distribution so that its average  $\langle \log \lambda_{ij} \rangle \approx 0$  and its spreading is 64%. Note that the random complex order of unity factors which are supposed to multiply all the mass matrix elements are not presented here.

### 3 Fukugita and Yanagida scenario for the lepton number production

The weak  $SU(2)$  instantons [19] - sphaleron [20] - guaranteed the rapid exchanges of the baryon number and lepton number in which though  $B - L$  is conserved in the time of big bang, when the temperature was above the weak scale. But in our model we have the three right-handed neutrinos decaying in the  $L$  quantum number violating way, in fact also  $B - L$  violating way, at the time scale of the see-saw neutrinos. Therefore the baryon number violation condition of the first Sakharov's condition was effectively fulfilled.

The assumption in our model that all the coupling constants and coefficients are of *order of unity* and *random* at the Planck scale, especially having random phases as far as allowed, implies not only  $C$  violation but also  $CP$  violation.

Finally the third condition among the Sakharov conditions - out-of-equilibrium - comes about during the Hubble expansion due to the excess of the three type of the right-handed Majorana neutrinos caused by their masses. From these statements our model is seen to implement the scenario of Fukugita and Yanagida [17].

In the scenario favoured by our model the heaviest one among the three right-handed neutrinos turns out to give the dominant contribution to the baryon or rather  $(B - L)$  quantum produced with the second becoming almost same order magnitude. Also it turns out that the average lifetime of this heaviest right-handed neutrino is of the same order as the Hubble expansion time so that we can count that a major part of these right-handed neutrinos first decay after inverse decays have essentially stopped. We shall justify and discuss these features of the scenario induced by our model in the next subsection. But first we shall describe the appearance of the baryon asymmetry taking for granted the mentioned assumptions so that we (1) use only the heaviest right-handed neutrino and (2) assume it to live relatively long compared to the time needed before  $B - L$  is effectively conserved again. Really as we shall discuss more below, it is not the full  $B - L$  which is the important quantity but a special roughly speaking "third generation  $B - L$ " that is the sufficiently well conserved charge quantity.

#### 3.1 Conservation of the $B - L$ -quantum charge

*A priori* the excess of  $(B - L)$  quantum number risk to be diluted or washed out before the "accidental"  $(B - L)$  conservation of the SM sets in. It is therefore very important to argue for that such wash out does not take place.

An important point is that it actually will turn out that if we only thought in terms of  $(B - L)$  one would estimate an appreciable wash out. However, *we define a new "new charge"  $(\widehat{B - L})_3$  which<sup>1</sup> is washed away much more slowly.* In the era until the lightest right-handed neutrino has

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<sup>1</sup>Note that this  $(\widehat{B - L})_3$  is not exactly the same as the  $(B - L)_3$  in our model, the latter a proto  $(B - L)_3$  while

become so hard to produce that there are basically no more inverse decay processes producing it going on and also 2-by-2 scatterings are supposed negligible, we have effective conservation of the following charge  $(B - L)_3$ : we define  $(B - L)_3$  to be the baryon number minus the lepton number sitting on those leptons (or quarks) which are capable by collision with a Weinberg-Salam Higgs particle to produce, in resonance say, the heaviest of the right-handed neutrino, but not the two lighter ones.

It is the era when we can ignore diagrams involving the heaviest see-saw neutrino a “third generation” quark or lepton, *i.e.* not coupling to the vertices  $N_2 \phi_{WS} \ell$  or  $N_1 \phi_{WS} \ell$  cannot get converted in a  $(B - L)$ -violating way because the diagrams have to contain such vertices.

The protection against dilution by  $N_2$  and  $N_1$  effects of the by  $N_3$  produced  $(B - L)$  hoped for is thus not relying on our model having a gauged  $(B - L)_3$  but is a more general mechanism.

The question of whether the  $(B - L)$  quantum number produced in excess by the decays of the heaviest Majorana neutrino will be preserved for the future is thus the question of whether the temperature falls so deep that this right-handed heaviest neutrino itself gets so hard to produce that we can ignore its inverse decay before all these heaviest right-handed neutrinos have decayed except for a fraction of order unity. The time needed to make the heaviest right-handed neutrino effectively unproduceable is the Hubble time corresponding to the temperature being equal to the mass of this see-saw neutrino. The crucial parameter to settle if this approximation of sufficiently slow decay is thus the ratio

$$K_i \equiv \frac{\Gamma_i}{2H} \Big|_{T=M_i} = \frac{M_{\text{Planck}}}{1.66 \langle \phi_{WS} \rangle^2 8\pi g_{*i}^{1/2}} \frac{((M_\nu^D)^\dagger M_\nu^D)_{ii}}{M_i} \quad (i = 1, 2, 3) , \quad (5)$$

where  $\Gamma_i$  is the width of the flavour  $i$  Majorana neutrino,  $M_i$  is its mass and  $g_{*i}$  is the number of the degree of freedom at temperature  $M_i$  (see Eq. (7)).

### 3.2 Baryogenesis and $CP$ violation

Now a right-handed neutrino,  $N_R$ , decay into a Weinberg-Salam Higgs particle and a left-handed lepton or into the  $CP$  conjugate channel. These two channels have different lepton numbers  $\pm 1$ . But, because of our random complex couplings, the partial widths do not have to be the same to next-to-leading-order perturbation theory. Defining the measure  $\epsilon_i$  for the  $CP$  violation in the decay of the right-handed neutrino

$$\epsilon_i \equiv \frac{\Gamma_{N_{R_i} \ell} - \Gamma_{N_{R_i} \bar{\ell}}}{\Gamma_{N_{R_i} \ell} + \Gamma_{N_{R_i} \bar{\ell}}} , \quad (6)$$

where  $\Gamma_{N_{R_i} \ell} \equiv \sum_{\alpha, \beta} \Gamma(N_{R_i} \rightarrow \ell^\alpha \phi_{WS}^\beta)$  and  $\Gamma_{N_{R_i} \bar{\ell}} \equiv \sum_{\alpha, \beta} \Gamma(N_{R_i} \rightarrow \bar{\ell}^\alpha \phi_{WS}^{\beta\dagger})$  are the  $N_{R_i}$  decay rates (in the  $N_{R_i}$  rest frame), summed over the neutral and charged leptons (and Weinberg-Salam Higgs fields) which appear as final states in the  $N_{R_i}$  decays one sees that the excess of leptons over anti-leptons produced in the decay of one  $N_{R_i}$  is just  $\epsilon_i$ .

At high temperature ( $T \gtrsim M_3$ ) equilibrium there were as many Majorana neutrinos per species as massless fermions, SM fermions. In the case ( $T \gtrsim M_3$ ) all these Majorana neutrinos decay after the  $B - L$  violation is switched off.

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$(B - L)_3$  deviates by mixing angles from the first one.

To be able to calculate Baryogenesis we need to obtain the total number of effectively massless degree of freedom of the plasma,  $g_{*i}$ , at temperature of the order of lightest right-handed neutrino (about  $10^6$  GeV), *i.e.*, there are 14 bosons and 45 well-known Weyl fermions plus  $i$  Majorana particles:

$$\begin{aligned}
g_{*i} &= \sum_{j=\text{bosons}} g_j \left(\frac{T_j}{T}\right)^4 + \frac{7}{8} \sum_{j=\text{fermions}} g_j \left(\frac{T_j}{T}\right)^4 \\
&= \underbrace{28 + \frac{7}{8} \cdot 90}_{\text{Standrad Model}} + \underbrace{\frac{7}{4} \cdot i}_{\text{see-saw particles}} \\
&= \begin{cases} 108.5 & : i = 1 \\ 110.25 & : i = 2 \\ 112 & : i = 3 \end{cases}, \tag{7}
\end{aligned}$$

here  $T_j$  denotes the effective temperature of any species  $j$ . When we have coupling as at the stage discussed between all the particles  $T_j = T$ . The entropy of Planck radiation with the degree of freedom  $g_{*i}$  is

$$s_i = \frac{2\pi^2 g_{*i}}{45} T^3. \tag{8}$$

Moreover, we should note here that due to the electroweak sphaleron effect, the baryon number asymmetry  $Y_B$  is related to the lepton number asymmetry  $Y_L$  by [21]:

$$\begin{aligned}
Y_B &= a Y_{B-L} = \frac{a}{a-1} Y_L \\
\text{with } a &= \frac{8N_f + 4N_H}{22N_f + 13N_H},
\end{aligned}$$

where  $N_f$  is the number of generations and  $N_H$  the number of Higgs doublets, this reads in the SM  $a = 28/79$ .

Because  $K_i$  is not small, we have to expect a dilution effect for which we define the suppression factor  $\kappa_i$ , *i.e.* we define  $\kappa_i$  so that the resulting relative to entropy density,  $s_i$ , baryon number density

$$Y_B \equiv \left| \sum_{i=1}^3 \kappa_i \frac{\epsilon_i}{g_{*i}} \right|. \tag{9}$$

A good approximation for  $\kappa_i$ , the dilution factor, is inferred from Ref. [22, 23]:

$$10 \lesssim K_i \lesssim 10^6 : \quad \kappa_i = -\frac{0.3}{K_i (\ln K_i)^{\frac{3}{5}}} \tag{10}$$

$$1 \lesssim K_i \lesssim 10 : \quad \kappa_i = -\frac{1}{2 K_i}, \tag{11}$$

$$0 \lesssim K_i \lesssim 1 : \quad \kappa_i = -\frac{1}{6}. \tag{12}$$

Note that these dilution factors – we are taking it – contain the effect of the sphaleron processes we should use, instead of the Eq. (17) and Eq. (18), we took the following interpolating redefined

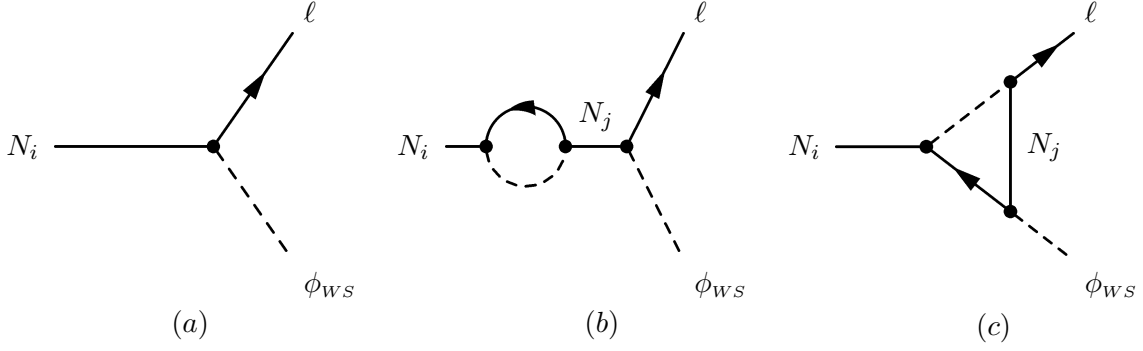


Figure 1: Tree level (a), self-energy (b) and vertex (c) diagrams contributing to heavy Majorana neutrino decays.

dilution factor in the range  $0 \lesssim K_i \lesssim 10$ :

$$0 \lesssim K_i \lesssim 10 : \quad \kappa_i = -\frac{1}{2\sqrt{K_i^2 + 9}} \quad (13)$$

Since this dilution factor is smoother than the in the Ref. [22] defined one, and due to using order-of-one complex random factors in calculation of  $K_i$ 's, especially in our model, baryogenesis comes mainly from the third Majorana neutrino decay, *i.e.* the calculation of the  $K_3$  have to be carefully performed because of  $K_3 \approx 1$ , therefore we should better use the newly defined smoothed out  $\kappa_i$  in Eq. (19).

### 3.3 $CP$ violation in decays of the Majorana neutrinos

The total decay rate at the tree level (Fig. 1–(a)) is given by

$$\Gamma_{N_i} = \Gamma_{N_i \ell} + \Gamma_{N_i \bar{\ell}} = \frac{((M_\nu^D)^\dagger M_\nu^D)_{ii}}{4\pi \langle \phi_{ws} \rangle^2} M_i \quad . \quad (14)$$

The  $CP$  violation in the Majorana neutrino decays,  $\epsilon_i$ , arises when the effects of loop are taken into account, and at the one-loop, the only  $CP$  asymmetry of the vertex contribution comes from the diagram shown in Fig. 1–(c). However there is an other contribution, from the wave function renormalisation (Fig. 1–(b)), which must be also taken into account and which gives typically same order amount as the vertex one [24, 25, 26]:

$$\epsilon_i = \frac{1}{4\pi \langle \phi_{ws} \rangle^2 ((M_\nu^D)^\dagger M_\nu^D)_{ii}} \sum_{j \neq i} \text{Im}[(M_\nu^D)^\dagger M_\nu^D]_{ji}^2 \left[ f\left(\frac{M_j^2}{M_i^2}\right) + g\left(\frac{M_j^2}{M_i^2}\right) \right] \quad (15)$$

where the function,  $f(x)$ , comes from the one-loop vertex contribution and the other function,  $g(x)$ , comes from the self-energy contribution. These functions can be calculated in perturbation theory only for differences between Majorana neutrino masses which are sufficiently large compare to its



decay widths, *i.e.* the mass splittings satisfy the condition,  $|M_i - M_j| \gg |\Gamma_i - \Gamma_j|$ :

$$f(x) = \sqrt{x} \left[ 1 - (1+x) \ln \frac{1+x}{x} \right] , \quad (16)$$

$$g(x) = \frac{\sqrt{x}}{1-x} . \quad (17)$$

## 4 Baryogenesis calculation in Anti-GUT model

In this section we present the calculation of the baryogenesis at first numerically, and then in a crude way by seeking the dominating terms.

The calculation goes by using formula (15), (16) and (17) taking as the mass matrix  $M_\nu^D$ , the expression (3), with each matrix element further provided with an (independent of the other matrix elements) random complex number of order unity. Also the right-handed neutrino masses to be used as  $M_i$  ( $i = 1, 2, 3$ ) in the functions  $f$  and  $g$  in formulas (16) and (17) are (in principle) calculated by inserting random numbers of order unity into, in this case, the right-handed neutrino mass matrix (4), in the way that each matrix element is again provided with an order of unity random (complex) factor. These random order unity coefficients are in the calculation taken as complex pseudo-random numbers.

The quantity  $\epsilon_i$  is then calculated 100,000 times and its logarithm,  $\ln|\epsilon_i|$ , is averaged over the different sets of random numbers. And the parameters which are the suppression factors  $S, W, T, \xi, \chi$  and  $\phi_{B-L}$  are taken for the best cases of our previous article fitting the neutrino masses and its mixing angles:

$$\begin{aligned} \langle \phi_{WS} \rangle &= \frac{246}{\sqrt{2}} \text{ GeV} , \quad \langle \phi_{B-L} \rangle = 2.74 \times 10^{12} \text{ GeV} , \quad \langle S \rangle = 0.721 , \\ \langle W \rangle &= 0.0945 , \quad \langle T \rangle = 0.0522 , \quad \langle \xi \rangle = 0.0331 , \quad \langle \chi \rangle = 0.0345 , \end{aligned} \quad (18)$$

where the vacuum expectation values, except the Weinberg-Salam Higgs and  $\langle \phi_{B-L} \rangle$ , are presented in the Planck unit.

That is to say we really use  $S, W, T, \xi, \chi$  and  $\phi_{B-L}$  from one of the best fits including the factorial corrections to the charged lepton and quarks, while  $\chi$  and  $\phi_{B-L}$  are fitted to the neutrino oscillation data. Since our model unavoidable predicts the small mixing angle MSW solution, our calculation is not meaningful unless the SMA solution is right. But recently Barbieri and Strumia [27] have studied the neutrino oscillation fit using “non-standard analogies” method and have shown that the region of the SMA-MSW solution should be shifted in the direction of smaller mixing angle, so that it escapes the day-night effect exclusion by the Super-Kamiokande measurements.

### 4.1 Results

Our total baryogenesis is a sum of three contributions, one from each see-saw particle. The total baryon density-to-entropy density ratio is given by

$$Y_B \equiv \left| \sum_{i=1}^3 Y_{B,i} \right| = \left| \sum_{i=1}^3 \kappa_i \frac{\epsilon_i}{g_{*i}} \right| , \quad (19)$$

where  $Y_{B,i}$  is the contribution due to the decay see-saw neutrino number  $i$  counted upwards in mass.

Dominantly the signs of  $\epsilon_3$  and  $\epsilon_2$  are strongly correlated but since the  $\epsilon_3$ -contribution is diluted away it does not matter and the danger of cancellation is not there. Actually we included in the numerical calculation the correlation of signs effects correctly. In our case the contribution of  $Y_{B,3}$  is dominant and the other contributions are negligible compared to  $Y_{B,3}$ . This makes the scheme opposite to SUSY constraint ones.

The numerical results of our best fitting case gives

$$|\epsilon_3| = 6.8 \times 10^{-9} , \quad K_3 = 1.06 \quad (20)$$

$$|\epsilon_2| = 6.0 \times 10^{-9} , \quad K_2 = 4.29 \quad (21)$$

$$|\epsilon_1| = 4.8 \times 10^{-10} , \quad K_1 = 19.8 . \quad (22)$$

Using the philosophy of letting order unity random numbers being given by a Gaussian distribution presented in the article [28] we estimate the uncertainty in the natural exponent for  $Y_B$  to be  $64 \% \cdot \sqrt{7} \approx 150 \%$ . With these error estimations we get

$$Y_B = 1.46^{+5.87}_{-1.17} \times 10^{-11} . \quad (23)$$

## 5 Conclusion and resumé

We have obtained with the cosmological fit,

$$Y_B |_{\text{experiments}} = (0.1 - 1.0) \times 10^{-10} , \quad (24)$$

Table 2: Typical fit including averaging over  $\mathcal{O}(1)$  factors. All quark masses are running masses at 1 GeV except the top quark mass which is the pole mass.

	Fitted	Experimental
$m_u$	3.1 MeV	4 MeV
$m_d$	6.6 MeV	9 MeV
$m_e$	0.76 MeV	0.5 MeV
$m_c$	1.29 GeV	1.4 GeV
$m_s$	390 MeV	200 MeV
$m_\mu$	85 MeV	105 MeV
$M_t$	179 GeV	180 GeV
$m_b$	7.8 GeV	6.3 GeV
$m_\tau$	1.29 GeV	1.78 GeV
$V_{us}$	0.21	0.22
$V_{cb}$	0.023	0.041
$V_{ub}$	0.0050	0.0035
$J_{CP}$	$1.04 \times 10^{-5}$	$2 - 3.5 \times 10^{-5}$

excellently agreeing prediction of the baryon number-to-entropy ratio

$$Y_B = 1.46^{+5.87}_{-1.17} \times 10^{-11} , \quad (25)$$

from our extended Anti-GUT under use of parameters all already fit to either the charged lepton and quark spectra or to the neutrino oscillations.

Even the “discrete fitting” of the precise choice of discrete quantum numbers of the seven Higgs fields  $\phi_{WS}$ ,  $S$ ,  $W$ ,  $T$ ,  $\xi$ ,  $\chi$  and  $\phi_{B-L}$  of our model were fit already to the mass and mixing angle data.

It should be remarked that our model predicts all fermion masses (neutrino mass square difference ratio) and their mixing angles, including Jarlskog triangle, using above presented seven Higgs VEVs (The quarks and charged lepton mass spectra and their mixing angles are presented in Table 2.):

$$\frac{\Delta m_{\odot}^2}{\Delta m_{\text{atm}}^2} = 5.8^{+30}_{-5} \times 10^{-3} \quad (26)$$

$$\tan^2 \theta_{\odot} = 8.3^{+21}_{-6} \times 10^{-4} \quad (27)$$

$$\tan^2 \theta_{e3} = 4.3^{+11}_{-3} \times 10^{-4} \quad (28)$$

$$\tan^2 \theta_{\text{atm}} = 0.97^{+2.5}_{-0.7} \quad (29)$$

*i.e.* our predictions are compatible with the MSW-SMA solar neutrino solution. Because of smallness of the Cabibbo angle induces our solar mixing angle to be so small that it would stress the model drastically to seek to fit one of the series of large solar mixing angle fitting regions.

All of the input parameters are, seven Higgs VEVs, already determined before the calculation of baryogenesis, so in this sense the baryon number-to-entropy ratio is pure prediction from our model!

The number of measured quantities which are predictable with our model, quark and charged lepton masses and its mixing angles including the Jarlskog triangle area  $J_{CP}$  and also two mass square differences for the neutrino and the three of their mixing angles, is 19. Our model successfully predicted all these quantities using only six parameters<sup>2</sup>: the genuine number of predicted parameters is thus 13. But we have taken into the predictions the quantity  $\tan^2 \theta_{13}$  for which CHOOZ has only an upper bound.

It should, however, be admitted that our prediction is *only order of magnitude-wise* because we needed to use the assumption that all the coupling constants at the fundamental scale are of order unity.

## 5.1 What do we learn?

In the crudest approximation our agreement means that the general success of getting good baryon number prediction from the Fukugita-Yanagida scheme of having  $B$  asymmetry from the

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<sup>2</sup>The VEV of Weinberg-Salam we have not counted as a parameter because of the relation to the Fermi constant.

see-saw scale works well with our specific model. This very good agreement of our prediction, of course, suggests that our specific model may carry some truth. It is first of all via the  $CP$ -violating parameter,  $\epsilon$ , that different detailed models can make their differences felt since even a supersymmetric model doubling of  $g_*$  is only a factor 2 hardly distinguishable with our only order of unity accuracy.

We expect the  $\epsilon$  which is an expression for the overall size of the Yukawa couplings – it is a loop effect relative to the tree diagram – for given mass splitting – for charged leptons and quarks to be sensitive to the number of effective charges in the model used for the mass protections. Indeed we expect more general suppression and therefore smaller  $\epsilon$  and thus baryon number if we imagined to have control over the  $\kappa_i$ 's – the bigger the number of charge types used.

When our model then gives a good baryon number result we should expect that its number of charges species – effectively – used is roughly right. Since our model has in fact under some restrictions the maximal number of gauge charges the success of predicting  $\epsilon$  suggests that the right model should have a rather large number of charges species. It should, however, in this connection be reminded that since we have the field  $S$  giving only a tiny suppression the tree group we have “effectively” used is not the full Anti-GUT one but rather the subgroup of it obtained after breaking by  $S$ ,  $SU(3)^2 \times SU(2)^2 \times U(1)^5$ .

It should be also be mentioned that it was in our Anti-GUT put in, that the representations of the non-abelian subgroups  $SU(3)$  and  $SU(2)$  were given by a rule <sup>3</sup> from those of the abelian, so that the non-abelian ones play no separate role. We did not even list the non-abelian representations in Table 1.

Moreover, it should be stressed that our scenario is very different from the SUSY model one: in SUSY model or SUGRA there is the problem that gravitinos survive and cause an unacceptable mass density contribution unless their production does not occur due to late inflation [29]. This makes it a problem to obtain the  $B - L$  from the see-saw neutrino decays and more problematic the heavier the right-handed neutrino used. This is why Buchmüller and Plümacher [25] have the lightest of the right-handed neutrino provide the baryogenesis.

Since our model is a non-SUSY one we have no gravitino problem and thus we could equally well make use the heavier Majorana neutrinos as of only the light one.

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<sup>3</sup>The rule is that the representation of the family specific  $SU(2)_i$  and  $SU(3)_i$  gauge groups are obtained as the same ones as a quark or lepton in the SM has when its weak hypercharge  $y/2$  equals  $y_i/2$ .

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